

## SURFACE MEASUREMENTS OF SHEAR WAVE VELOCITY AT THE 7-GeV APS SITE

### 1.0 INTRODUCTION

A knowledge of shear wave speeds as a function of site location and soil depth is fundamental to the vibration study of the 7-GeV Experiment Hall foundation supporting the storage ring magnets, insertion devices, and experiments. Among other things, knowledge of the shear wave speed allows one to calculate the shear modulus of elasticity of the soil using the relationship

$$G = \rho V_S^2 \quad (1)$$

where  $G$  is shear modulus of elasticity,  $\rho$  is soil density, and  $V_S$  is shear wave speed. The shear modulus, in turn, is one of the most important parameters in performing a dynamic analysis of the response of the foundation to both external excitation (ground motion) and excitation sources internal to the Experiment Hall.

Shear (S) wave speed, as well as compression (P) wave speed, is typically determined from crosshole seismic testing [1]. The procedure is to use an energy source, receivers, and a recording system. The energy source and receivers are placed at the same elevation in drilled and cased boreholes, which are spaced 10 to 15 feet apart. Measurements are made at prescribed depth increments. Wave speeds are determined using the spacing between receivers and the arrival times of the different waves as obtained from response-time plots. As part of a geotechnical investigation of the 7-GeV APS site, the APS Project has contracted to have crosshole seismic testing performed. These tests are scheduled for early in calendar year 1988.

To provide early insight into the dynamic characteristics of the soil, to obtain information that will supplement the crosshole seismic test data, and to develop experience and a reference for an internal review and interpretation of the results to be obtained by the geotechnical contractor, surface measurements of shear wave speeds were made at the 7-GeV APS site and are reported herein.

## 2.0 MEASUREMENT METHOD

The measurement method is based on the utilization of an energy source that is rich in the type of energy required to excite the particular wave of interest. For a shear wave, the source should transmit energy to the ground primarily by directionalized distortion. The energy source should also be repeatable and reversible [1]. A weighted wooden timber impacted at the end with a hammer blow provides such a source; the polarity of the source is reversed by impacting the opposite end. As will be shown later, the reverse polarity of the source greatly facilitates the identification of the S-wave.

The timber used in this study has cross-sectional dimensions of approximately 6-in. x 10-in. and a length of 7 feet. The timber was weighted by driving the front wheel of a truck up onto it. An 8-lb hammer was used to impact the ends.

Such an energy source excites horizontally polarized shear waves that are optimally sensed using receivers positioned on a line emanating from the center of the timber and perpendicular to it; receivers are horizontally oriented to detect motion in a direction parallel to the timber. A layout of the source and receivers is given in Fig. 1. The receivers are piezoelectric accelerometers mounted on 6-in. long, 1-in. diameter steel stakes driven into the ground [2]. The accelerometers are spaced 15-ft apart with the first

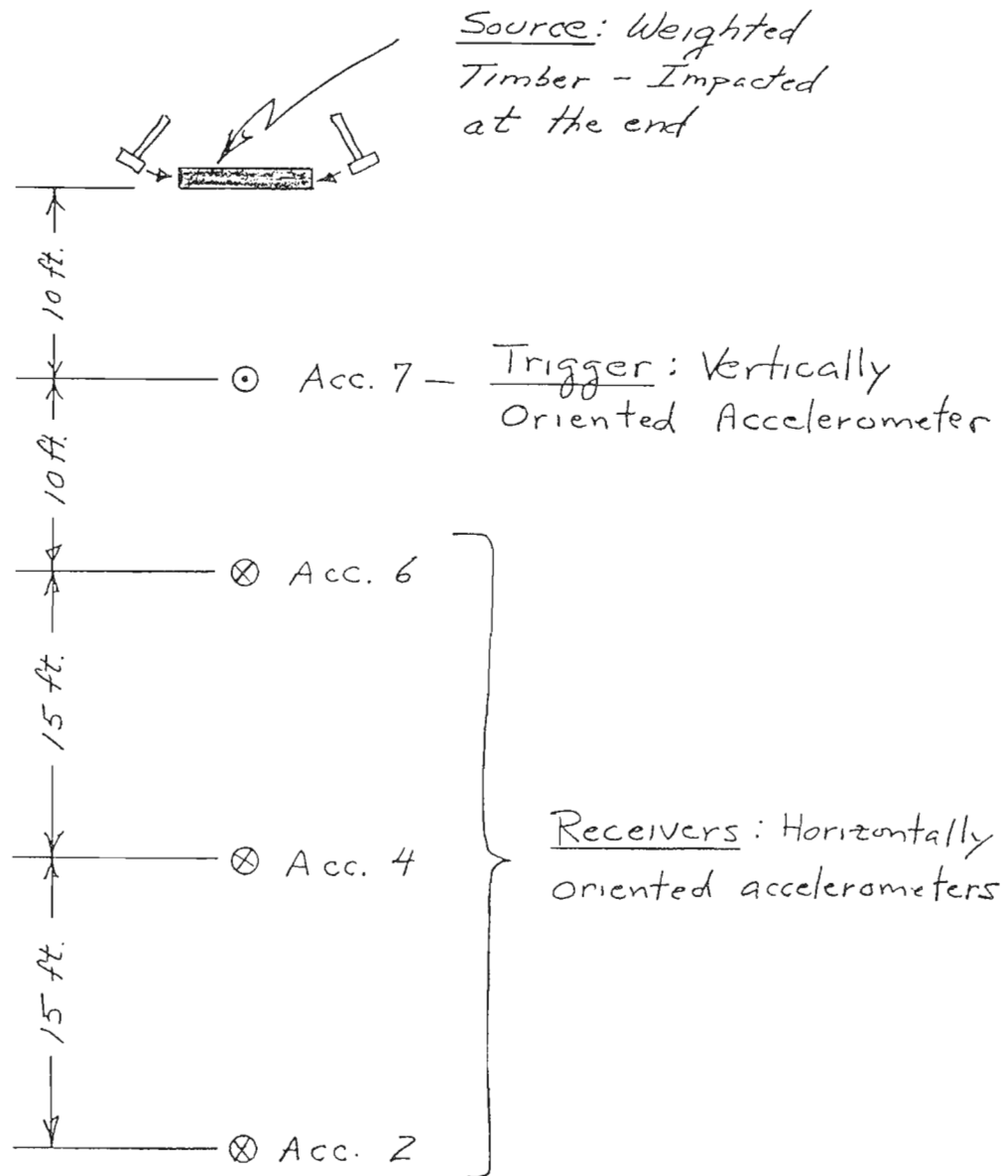


Fig. 1. Layout of source-trigger-receivers assembly

accelerometer 20-ft from the source. The accelerometers are connected to a battery-powered tape recorder [3].

A vertically-oriented accelerometer is located halfway between the source and first receiver to serve as a trigger. The trigger senses the passage of a wave and sends a signal to start the time analysis. For this application it is important to note that the trigger was set at a relatively high level to sense the passage of the Rayleigh wave, a large-amplitude, vertically-oriented wave with a fast rise time.

The test procedure consists of generating reverse polarity shear waves, first by impacting one end of the timber ( $\sim 10$  times in succession), and then by impacting the other end ( $\sim 10$  times). Acceleration-time traces, corresponding to each impact, are recorded on magnetic tape for subsequent processing and analysis.

A typical set of time records is given in Fig. 2. There are three pairs of traces, one pair from each of the three receivers (accelerometers). Each pair consists of reverse polarity shear waves. The S-wave arrival is determined where a  $180^\circ$  polarity change is noted to have occurred. As can be observed from Fig. 2, this technique allows for positive identification of the S-wave.

The shear wave speed is readily computed by dividing the distance between two pairs of receivers by the time for the signal to travel from the one receiver to the next. Travel times can be computed using the start of the S-wave, or any corresponding prominent feature on the time signals (e.g., zero crossing or peak), as the reference. As an example, using the traces given in Fig. 2 with the first zero crossing of the S-wave as the reference, the shear wave speed is calculated as follows:

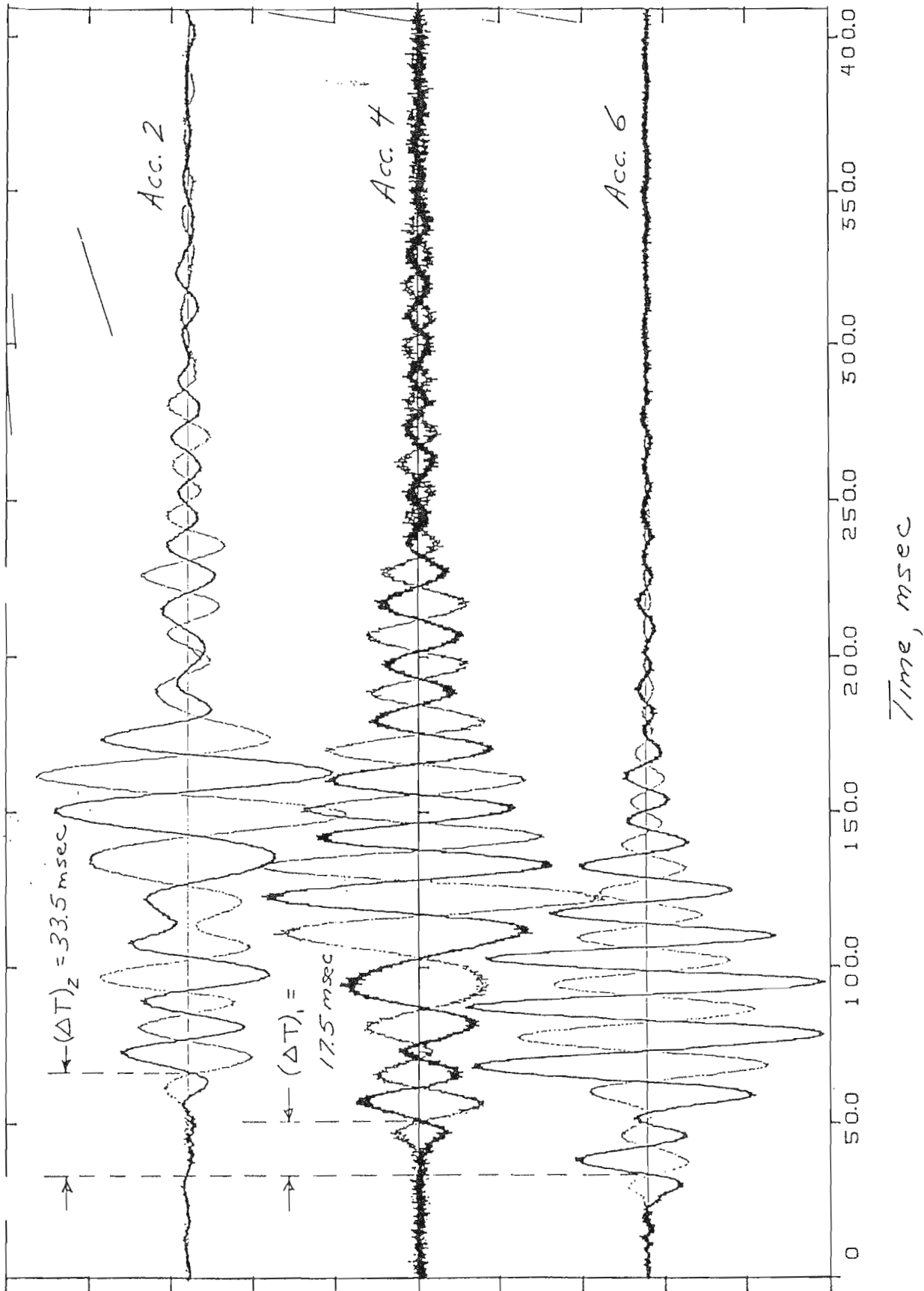


Fig. 2. Typical acceleration-time plots from Accelerometers 2, 4, and 6 (See Fig. 1 for orientation and spacing of receivers)

$$(V_S)_1 = \frac{(\Delta X)_1}{(\Delta T)_1} = \frac{15 \text{ ft}}{17.5 \times 10^{-3} \text{ sec}} = 857 \text{ ft/s}$$

$$(V_S)_2 = \frac{(\Delta X)_2}{(\Delta T)_2} = \frac{30 \text{ ft}}{33.5 \times 10^{-3} \text{ sec}} = 896 \text{ ft/s}$$

Taking the average obtains, for this example,

$$V_S = 876 \text{ ft/s} .$$

### 3.0 PRELIMINARY INVESTIGATION

Evaluation of the measurement method was accomplished by performing a preliminary investigation. A single set of measurements was made on August 5, 1987. The source-trigger-receivers system was set up on the west side of Building 335, between the building and the parking lot, as designated on the project area plan of Fig. 3 as location P.

The tests were performed following the procedure outlined in Section 2.0: shear waves were generated by impacting the end of the timber; reverse polarity waves were obtained by impacting the opposite end; the procedure was repeated ~ 10 times in each direction; with accelerometer 7 as a trigger, acceleration-time traces from receivers 2, 4, and 6 were obtained; random pairs of time traces, from pairs of reverse polarity waves, were plotted. The sample trace given in Fig. 2 is from the preliminary investigation.

The test results were independently analyzed by three evaluators. The average value of shear wave speed as determined by each of the three evaluators is given in Table 1. The computed values ranged from 866 to 945 ft/s, with a variation of (-4%, +5%) from the mean value of 897 ft/s.

Among other things, the preliminary investigation served to verify the use of reverse polarity waves as an excellent technique for positive

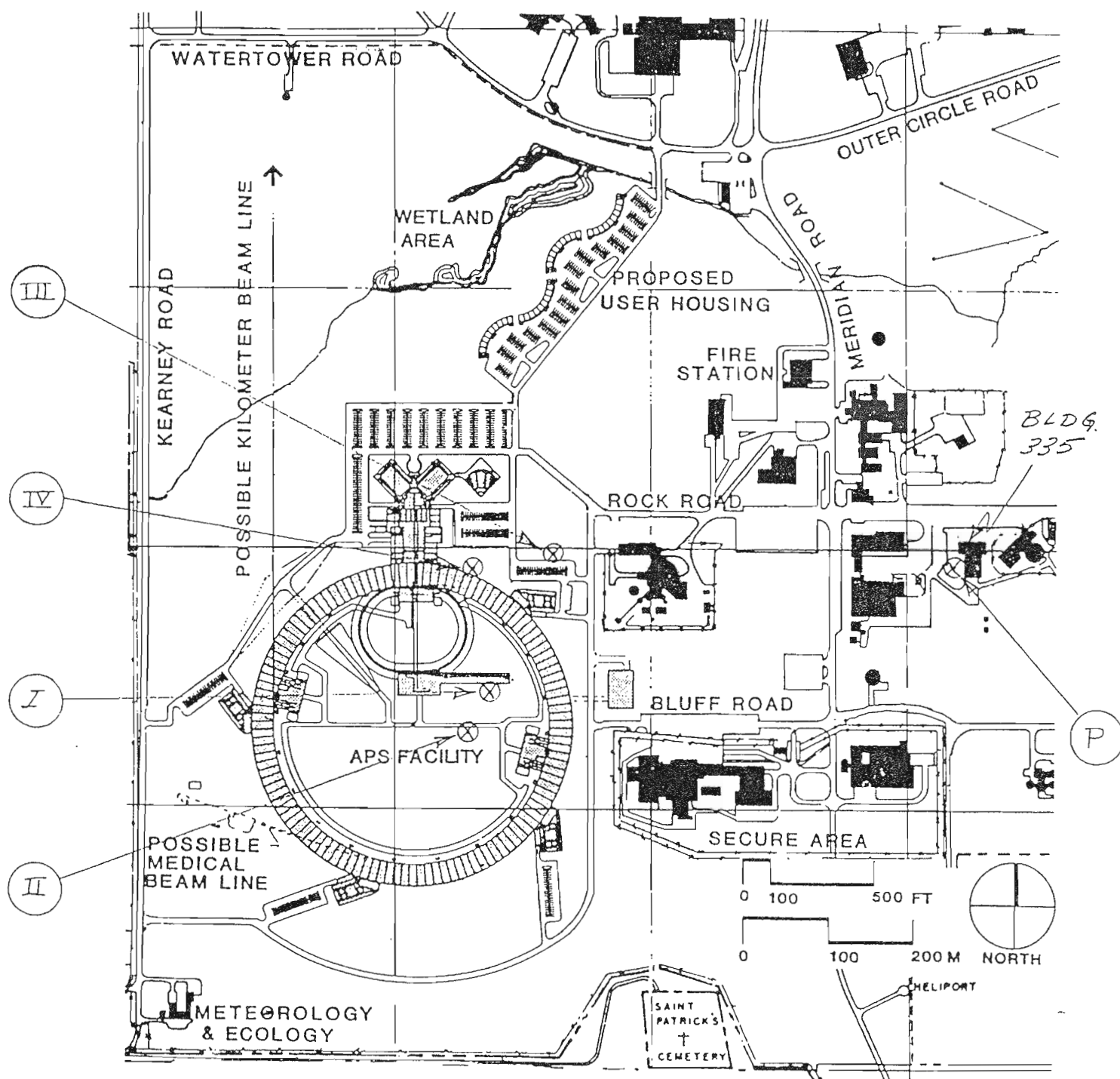


Fig. 3. Project area plan showing the measurement locations for the preliminary investigation (Location) and APS site investigation (Locations I-IV)

Table 1. Calculated shear wave speed (ft/s)

Evaluator*	Measurement Location				
	P	I	II	III	IV
FER	945	1131	1097	1244	990
JAJ	866	1082	1092	1206	908
MWW	880	1210	1070	1175	925
Avg	897	1141	1086	1208	941

\*FER  $\equiv$  F. E. Richart, Jr. (Consultant)  
JAJ  $\equiv$  J. A. Jendzejczyk (ANL)  
MWW  $\equiv$  M. W. Wambsganss (ANL)



identification of the shear wave from a time trace that includes compression and Rayleigh waves as well. Once the shear wave is identified, computation of wave speeds is straightforward using relative travel times. The study also showed that the time traces from different impacts are very repeatable, with subtle features repeating themselves in the different traces.

#### 4.0 SURVEY OF APS SITE

##### 4.1 Measurement Location

Having successfully demonstrated the measurement method, including data processing and interpretation, via the preliminary investigation described in Section 3, four measurement locations in the vicinity of the APS site were selected for a follow-on study. The four measurement locations, relative to the location of the APS Experiment Hall, are indicated on the project area plan given in Fig. 3. A brief description of the soil type at each of the measurement locations and the rationale for choosing that location are given below:

- ⊗ Location I - Dry, hard, yellow clay fill. This location was a dump site for fill. The fill was well packed. This site was selected since a segment of the 7-GeV APS Experiment Hall basemat may be constructed on fill of this type.
- ⊗ Location II - Very moist, soft, black soil. This location is just off Bluff Road, the East-West diameter of the storage ring. The soil type and condition is typical of that on which much of the Experiment Hall foundation will be constructed.
- ⊗ Location III - Miscellaneous fill site, including gravel, rock, and concrete - reasonably well packed. While outside of the circumference of the Experiment Hall, this location was chosen to

provide insight and a reference relative to the type of results one obtains from this contrasting soil type.

- Location IV - Very dark, very soft, extremely moist black soil. This location was selected because it represents essentially undisturbed soil that is typical of much of the soil in the vicinity of the base soil upon which the Experiment Hall foundation will be laid.

#### **4.2 Results**

The layout and relative orientation of the source-trigger-receivers system is the same as that used in the preliminary investigation and shown schematically in Fig. 1. The measurements were performed on August 24, 1987, following the procedure discussed in Section 2 and applied in carrying out the preliminary investigation described in Section 3. Typical sets of acceleration-time traces, one from each of four measurement locations, are given in Figs. 4-7 for Locations I-IV, respectively. As in the preliminary investigation, the shear wave is readily identified by the reverse polarity of the wave form.

#### **4.3 Interpretation of Results**

Again, the test results were independently analyzed by three evaluators. Average values of shear wave speed, as determined by each of the three evaluators, are given in Table 1 for each of the four measurement locations at the APS site.

In studying the data, it was observed, as can be noted on the acceleration-time traces given in Figs. 2, 4-7, that there appears to be a characteristic frequency associated with the acceleration-time signals. As noted in Section 2, the timber was weighted by running the front wheel of a truck up onto it. It was suggested that "...the elastic system of soil-timber

Loc 1

Sec 2

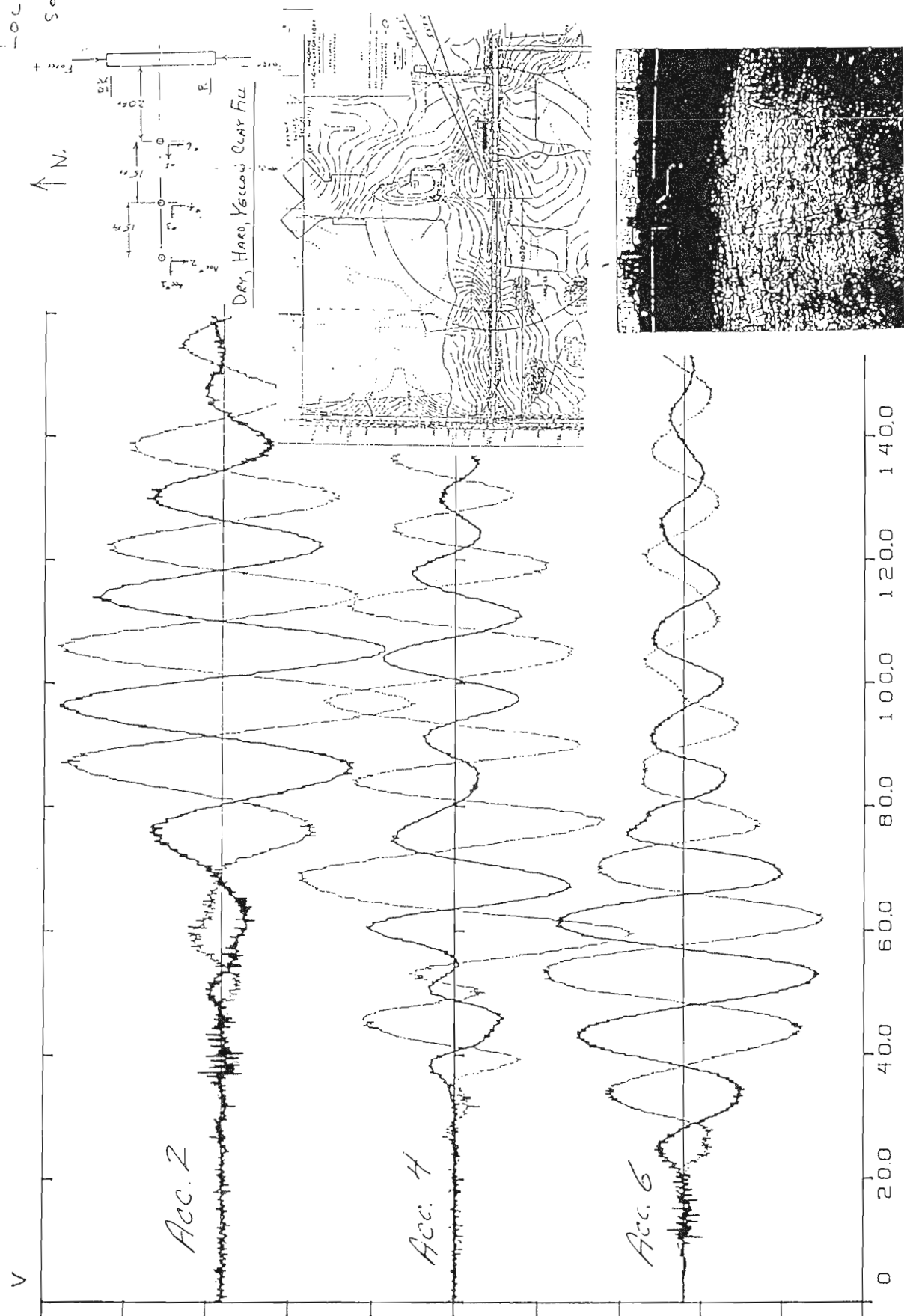


Fig. 4. Typical acceleration-time plots from measurement location I

212.6+  
Loc 2

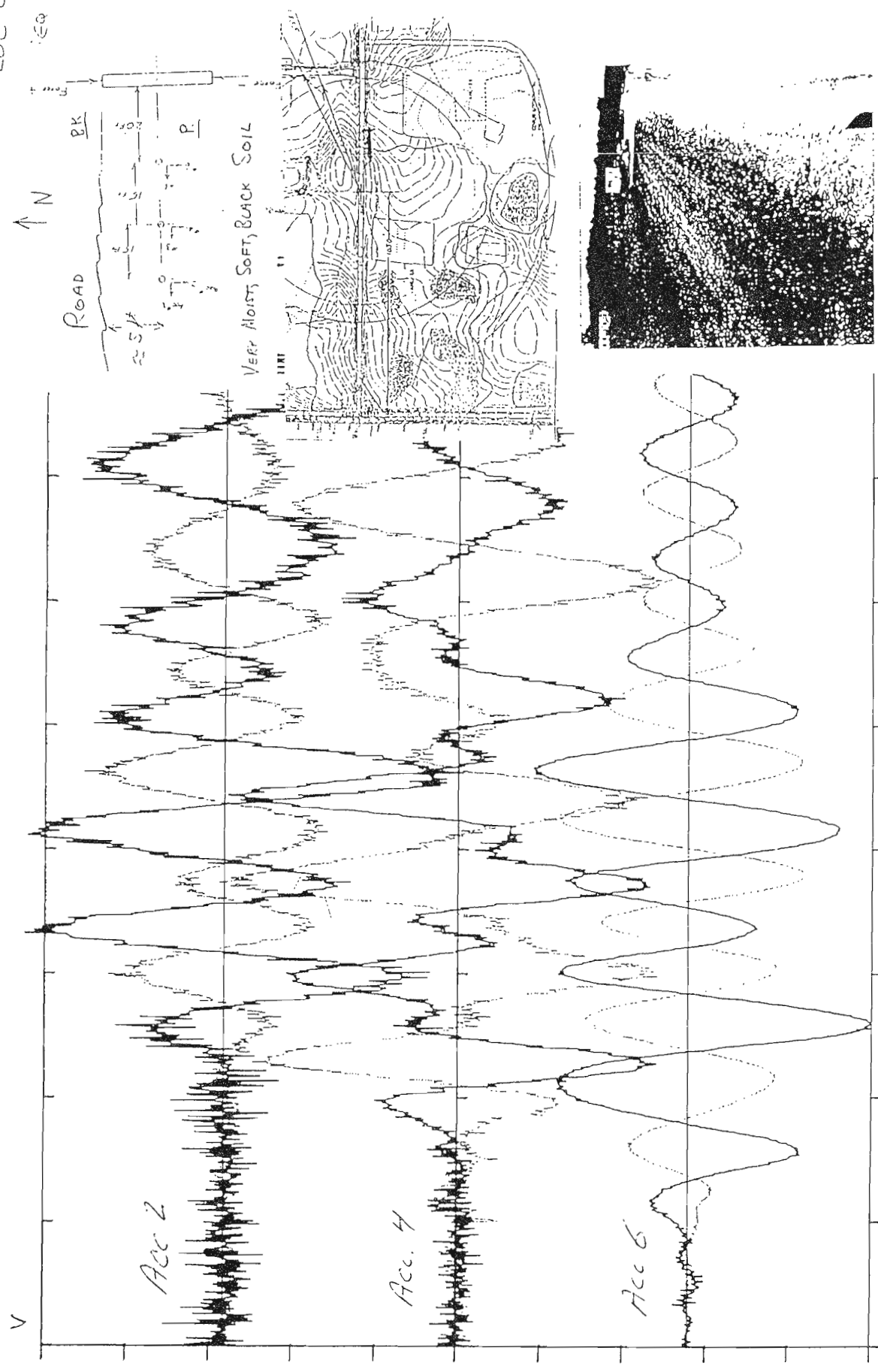


Fig. 5. Typical acceleration-time plots from measurement location II

6/1/77  
Loc. III

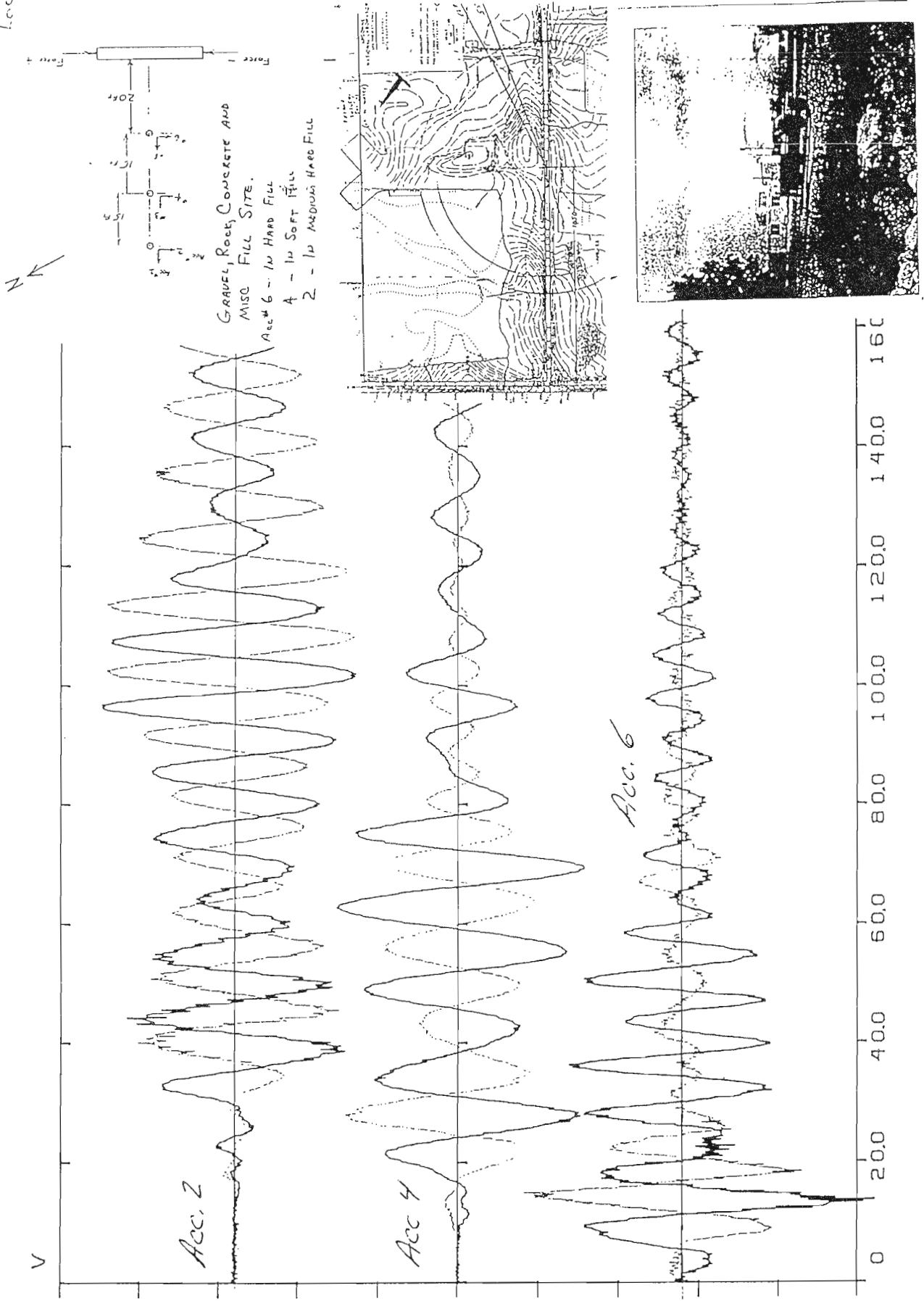


Fig. 6. Typical acceleration-time plots from measurement location III

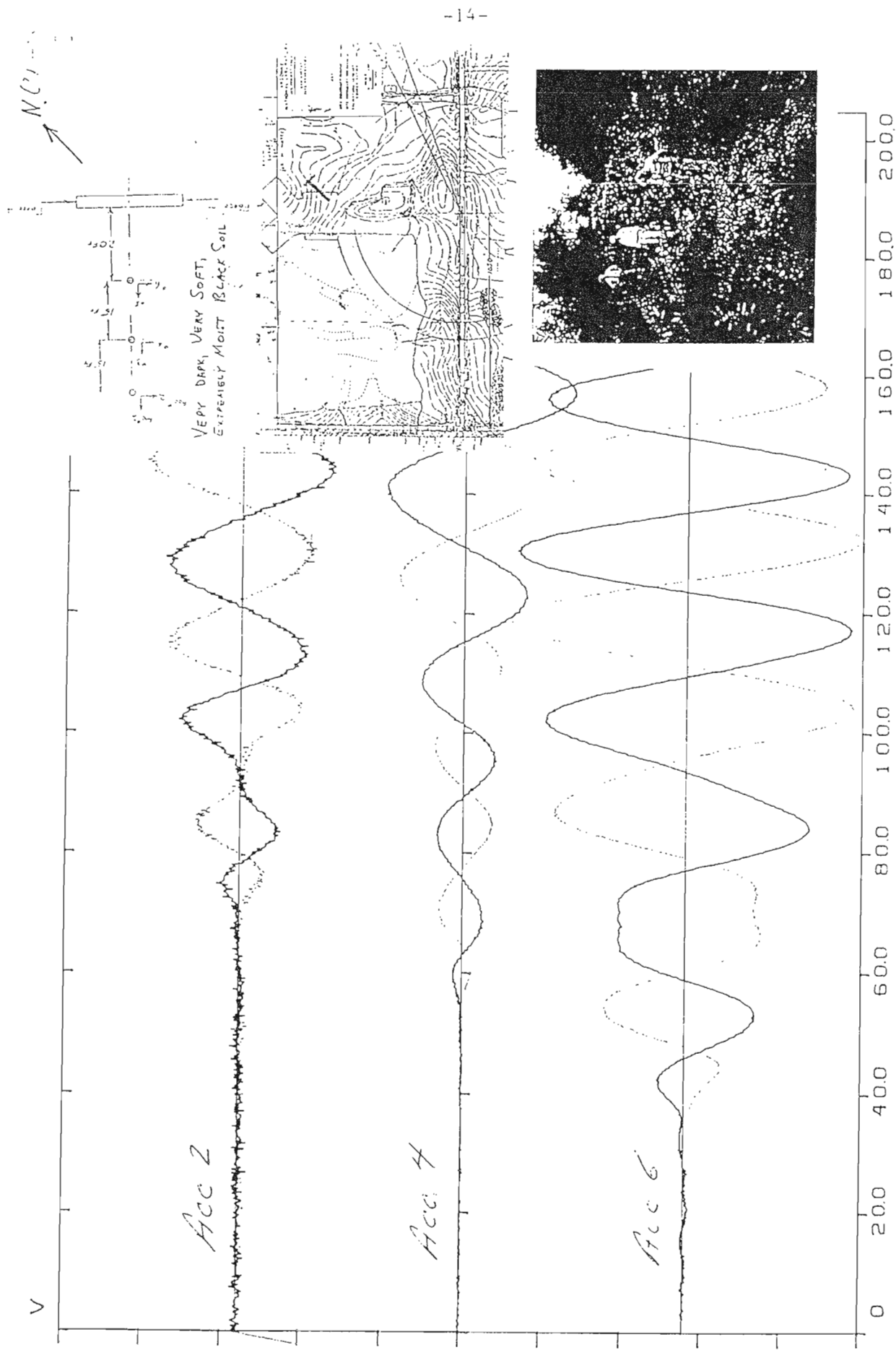


Fig. 7. Typical acceleration-time plots from measurement location IV

restraint, and the 'ringing' of the tire-spring-mass system of the front end of the truck could create these relatively high frequency vibrations" [4].

To gain further insight into this phenomenon, the acceleration-time signals were processed on a fast Fourier transform analyzer to obtain frequency response information. Frequency response plots for each of the four measurement locations are given in Fig. 8. In general, the observed frequencies can be related to the soil type: the harder the soil, the higher the frequency. This supports the hypothesis that the timber-soil-spring system is involved in determining the observed characteristic frequencies.

However, the variation in principal frequency with receiver position for the Location IV measurements (see Fig. 8c) indicates that the dynamic characteristics of the soil-receiver assembly are also a factor in determining the characteristic frequency of the signal. In this case the 6-in. receiver stakes were located in medium-hard, soft, and hard fill, and the principal frequencies were on the order of 95, 75, and 146 Hz, respectively. The correlation of principal frequency with soil type is clearly demonstrated by this set of measurements. At each of the other measurement locations the soil type is essentially uniform where the receiver stakes were set, and the principal frequencies associated with the various receivers are approximately the same at a given measurement location.

## 5.0 DISCUSSION

Comparisons of the shear wave speeds as determined by the three different evaluators can be made using the results given in Table 1. The ASTM Standard [1] suggests, with regard to precision and bias in interpretation of such data, that "... within-laboratory repeatability of  $5 \pm 2.5\%$  can be expected. The greatest contribution to variance is likely to be the operator's

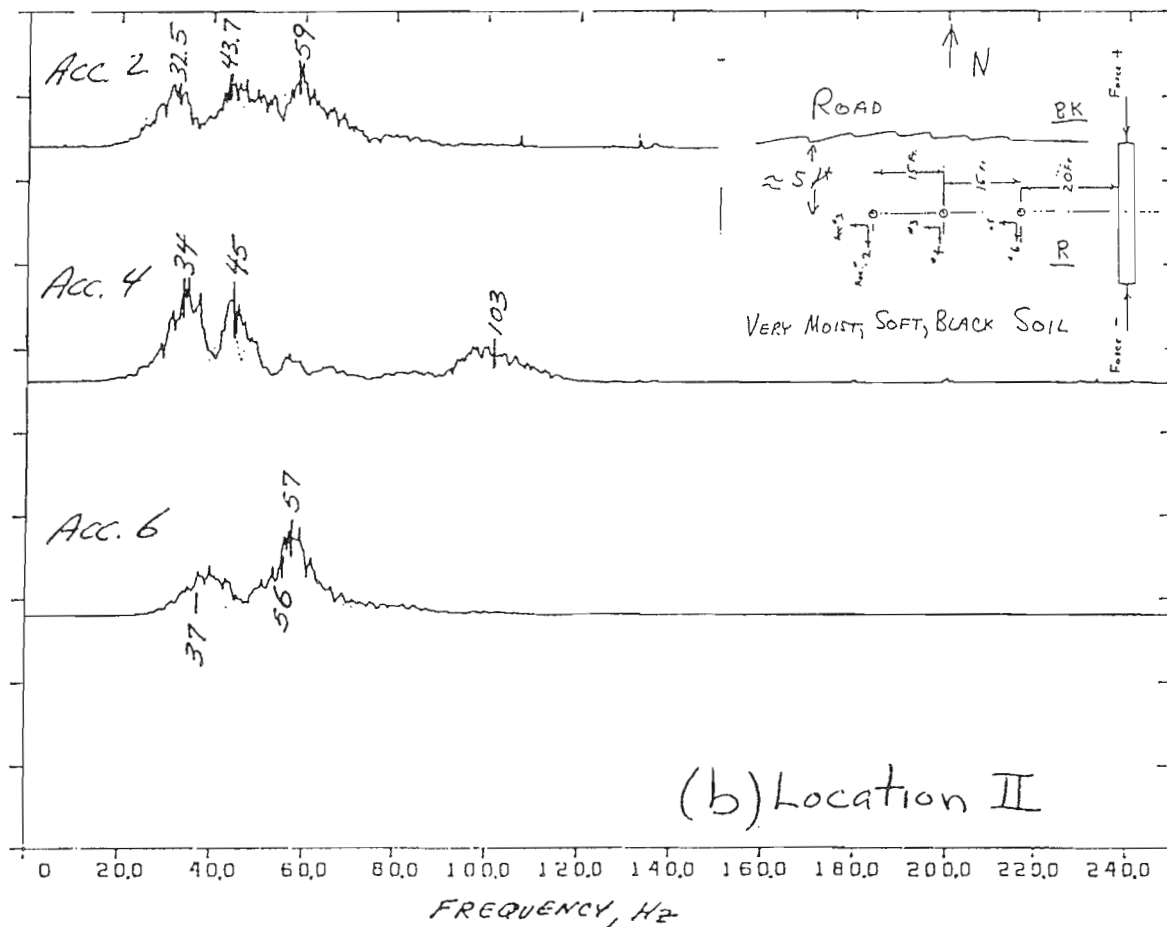
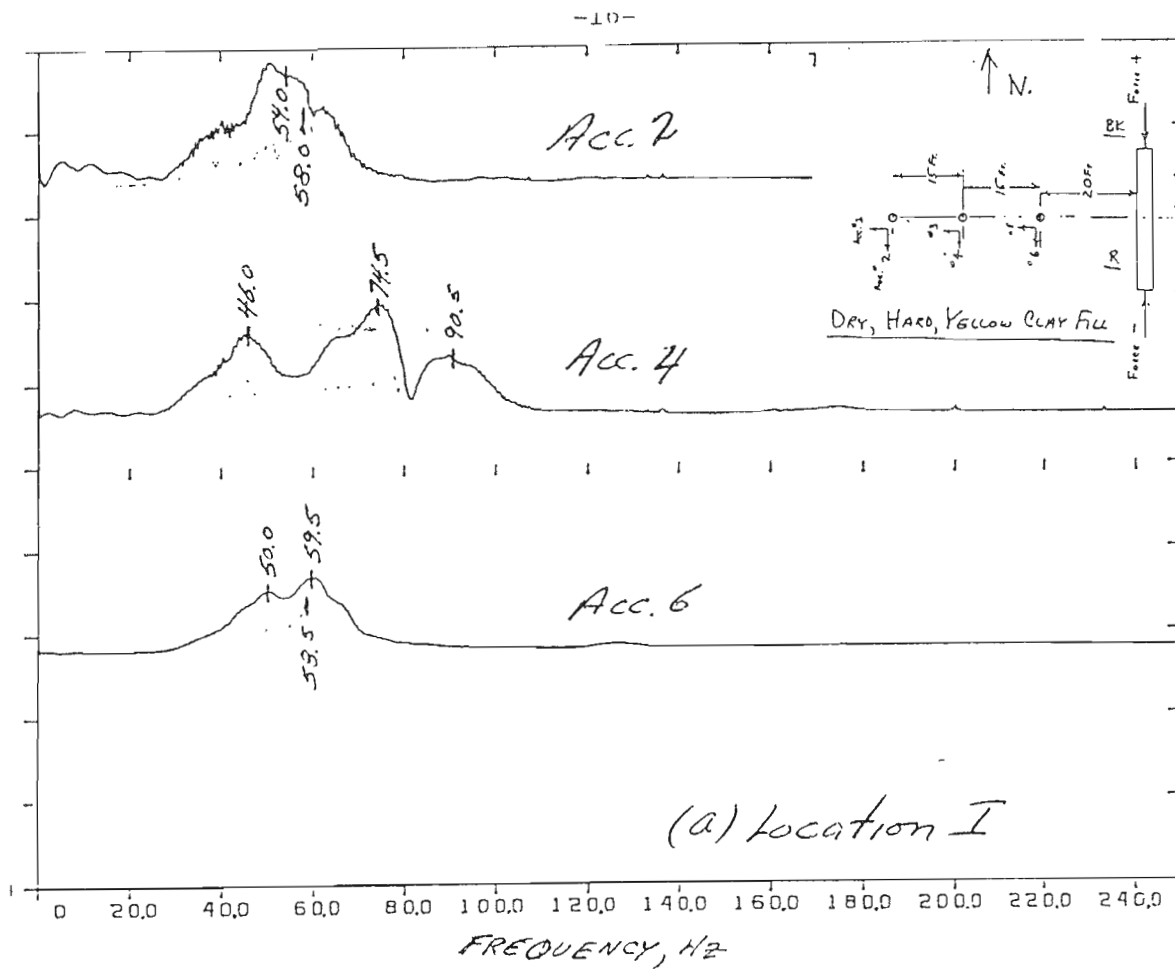


Fig. 8. Frequency content of acceleration-time signals  
(light line is reverse polarity wave signal)



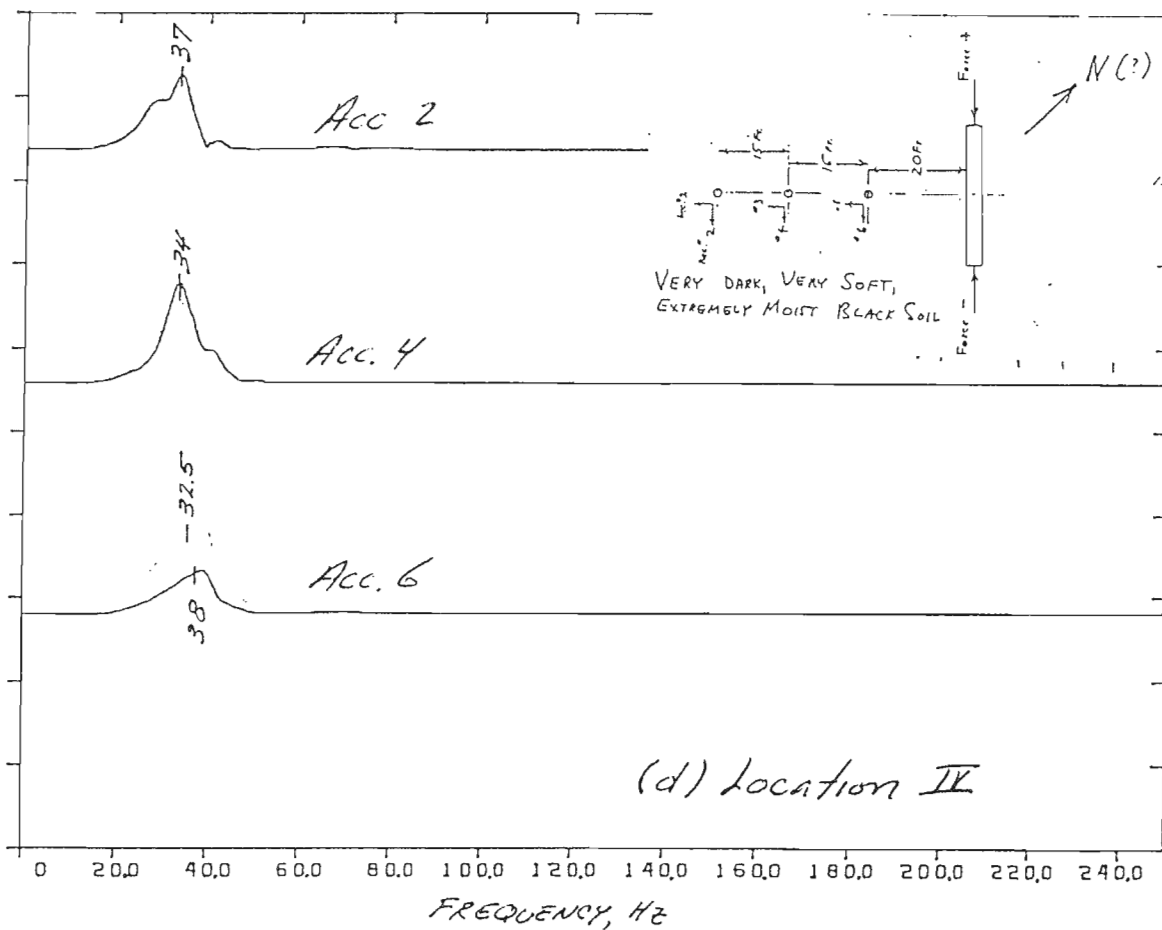
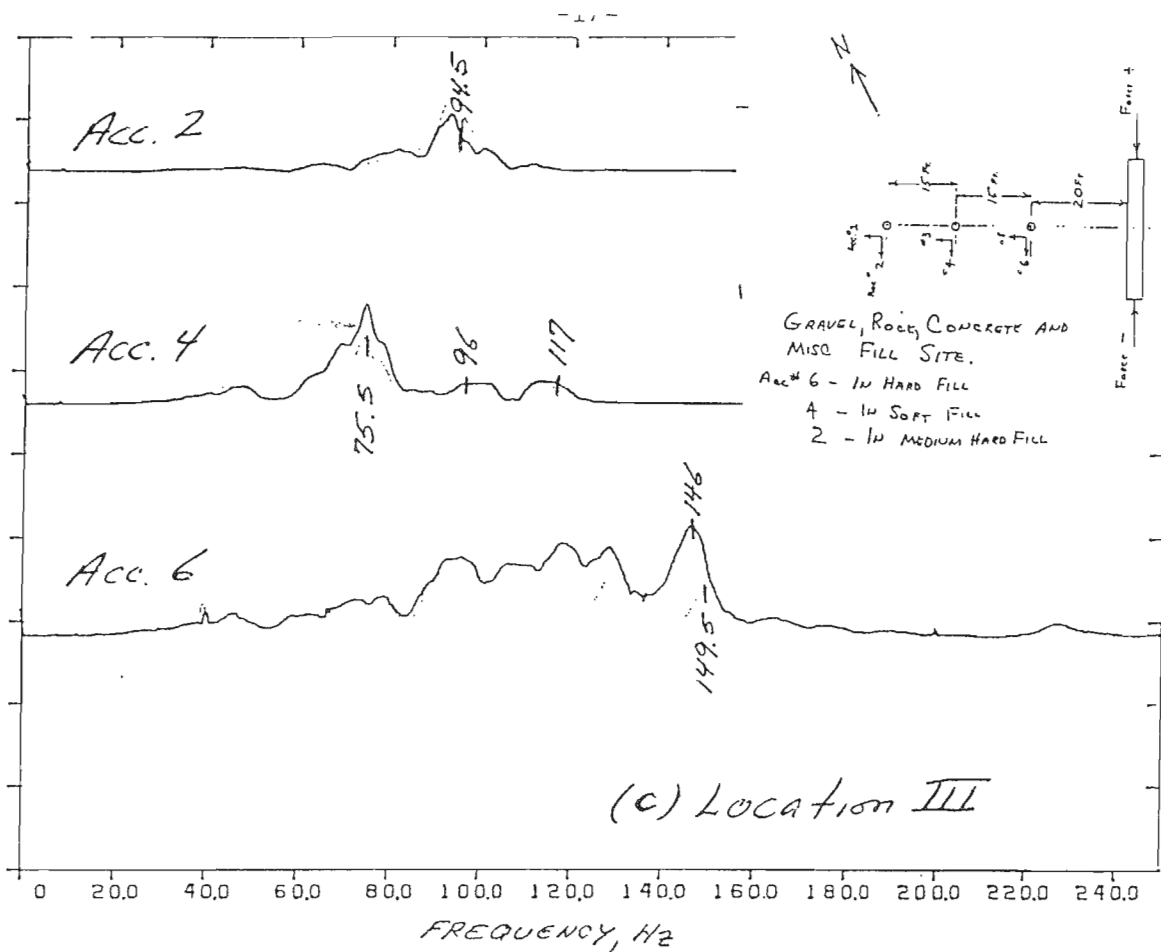


Fig. 8. (Cont'd.)

Frequency content of acceleration-time signals  
(light line is reverse polarity wave signal)

interpretation of arrival times." The maximum variance of the results presented in Table 1 (-5.2%, +6.0%) is within this range.

In Table 1, if we neglect the results of the preliminary investigation and the data from Location III, which is not typical of the APS site, we obtain the result that the shear wave speed, based on surface measurements, is in the range 940 to 1140 ft/s. It is known from a preliminary geotechnical investigation of the APS site that the average dry unit weight of the soil is 117 lb/ft<sup>3</sup>. Substituting this value, and the measured values of shear wave speeds, into Eq. (1) gives the result that the shear modulus of the soil is in the range  $2.2 \times 10^4$  lb/in.<sup>2</sup> to  $3.3 \times 10^4$  lb/in.<sup>2</sup>.

It has been demonstrated that, using an appropriate excitation/measurement method, shear waves can be readily identified on acceleration-time traces and shear wave speeds calculated. Surface measurements can be performed quickly and inexpensively with a minimal investment in equipment. The results provide early insight into the dynamic characteristics of the soil, provide the basis for a preliminary investigation of the vibration characteristics of the Experiment Hall foundation, and will supplement the data to be obtained from the planned crosshole seismic testing.

#### Acknowledgment

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References

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4. Letter, F. E. Richart, Jr., to M. W. Wambsganss, dated September 21, 1987.